10.00
File
#7848

NATIONAL BUREAU OF STANDARDS REPORT

7848

IGNITION OF SOME WOODS EXPOSED

TO LOW LEVEL THERMAL RADIATION

SECOND PROGRESS REPORT

By

A. J. Buschman, Jr.

NBS

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. Research projects are also performed for other government agencies when the work relates to and supplements the basic program of the Bureau or when the Bureau's unique competence is required. The scope of activities is suggested by the listing of divisions and sections on the inside of the back cover.

Publications

The results of the Bureau's research are published either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau publishes three periodicals available from the Government Printing Office: The Journal of Research, published in four separate sections, presents complete scientific and technical papers; the Technical News Bulletin presents summary and preliminary reports on work in progress; and the Central Radio Propagation Laboratory Ionospheric Predictions provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: Monographs, Applied Mathematics Series, Handbooks, Miscellaneous Publications, and Technical Notes.

A complete listing of the Bureau's publications can be found in National Bureau of Standards Circular 460, Publications of the National Bureau of Standards, 1901 to June 1947 ($1.25), and the Supplement to National Bureau of Standards Circular 460, July 1947 to June 1957 ($1.50), and Miscellaneous Publication 240, July 1957 to June 1960 (includes Titles of Papers Published in Outside Journals 1950 to 1959) ($2.25); available from the Superintendent of Documents, Government Printing Office, Washington 25, D.C.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT		NBS REPORT
1002-11-10427	April 5, 1963	7848

IGNITION OF SOME WOODS EXPOSED TO LOW LEVEL THERMAL RADIATION

SECOND PROGRESS REPORT

BY

A. J. Buschman, Jr.

FOR

Office of Civil Defense

OCD Project Order OCD-OS-62-89

NBS

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

IGNITION OF SOME WOODS EXPOSED TO LOW LEVEL THERMAL RADIATION

SECOND PROGRESS REPORT

By

A. J. Buschman, Jr.

ABSTRACT

Delayed ignition flame spread data by the radiant panel test are compared with standard flame spread and uniform flux data on a typical compressed cellulosic board. The importance of thermal conduction within a thin surface layer in the spread of flames is shown.

Results of tests performed to evaluate the effects of longitudinal thermal conduction are presented.

Surface temperatures were measured and the effect of the presence of the flame upon them determined. An attempt is made to show the possible compatibility of two ignition criteria, a minimum surface temperature and a minimum rate of volatile generation.

1. INTRODUCTION

The spread of flame over the surface of materials has been of interest in the field of experimental fire research for several years. Empirical tests are generally used to classify materials according to their flame spread behavior, two of the most common being a "tunnel" test [1], and a "radiant-panel" test [2]. It is the purpose of the present report to present the results of some experiments using the radiant-panel flame spread test in an effort to explain the mechanism by which a flame travels along a surface.

In the tunnel test a gas burner forces ignition at one end of a 25-ft long horizontal specimen which forms the "ceiling" of a tunnel furnace enclosure. The flame then travels along the specimen aided by the preheating effect of the burner flame itself in contact with the unignited portions. The heat input to the material prior to ignition is not known due to the complex radiative and convective transfer from the specimen and burner flames. The role of thermal conduction within the material is masked by the obscure flame front, complexities of the experimental arrangement, and the unknown heat input at the surface.

A variation of the tunnel-type test employs an enclosed 8-ft long specimen ignited by a small burner at its lower end and receiving supporting

thermal radiation from a steel plate separating the specimen from a gas-fired combustion chamber [3]. The specimen is inclined both lengthwise and across its short axis to simulate natural draft conditions.

The radiant panel test permits close observation of flame front progression on a much smaller specimen and with a minimum of convective and radiative feedback from the flames of the burning specimen. The geometry of the test apparatus provides a steady, low level, thermal irradiance to the 18-in. long specimen with maximum exposure at the top. A small pilot burner forces ignition at the top of the specimen and the flame front travels down the specimen succeeding portions of which are exposed to a continuously decreasing irradiation from the radiant panel. The flames from the burning portions do not brush over the unignited portions, and generally lie fairly close to the surface so that the thermal input to the unignited portions is primarily that received from the radiant panel.

Since flaming occurred on the surface at positions which were receiving less than the critical flux (irradiance) under uniform flux conditions [4], it appeared as though conduction both within the material and in the gas phase might be responsible for the more rapid flame travel. If tests were performed under conditions which completely removed the radiative and convective transfer by direct contact with the flames on the specimen surface, the role of thermal conduction within the specimen could be determined.

Prior to ignition, the problem is that of two-dimensional, unsteady-state heat transfer with non-linear boundary conditions. In the presence of a flame the problem becomes more complex due to heat transfer from a decelerating flame front. A complete analysis should also include the effects of self-heating due to the elevated temperatures in the vicinity of the flame front but this is probably a second order effect and will be neglected for the present.

The tests described in this report were made to gain a better understanding of particular aspects of the problem. They were not expected to present a complete solution but only to serve as a foundation upon which a better understanding of the entire problem could be formed.

2. EXPERIMENTAL DETAILS

A twelve by eighteen inch, vertical, gas-fired, refractory panel, described in detail in reference 2, was used as the source of radiant energy. During most of the tests, the radiant flux output of the panel corresponded to that of a blackbody at a temperature of 670°C. A few tests were performed with a panel blackbody temperature of 482°C. The gas supply to the panel was controlled manually and the temperature was monitored before each test with a calibrated radiometer.

Specimen size was six by eighteen inches unless otherwise stated. The material selected was a commercial wood-base hardboard* of fairly uniform surface flammability; asbestos millboard of comparable density** served as an inert material. All specimens were conditioned at 24°C and 50 percent relative humidity for at least 48 hours prior to any test.

Specimen thickness, unless otherwise specified, was one-quarter of an inch. Some tests to determine the effect of specimen thickness employed a range of thickness from 0.070 to 1.0 in.

3. RESULTS

3.1 Delayed Ignition Tests

The results of a series of delayed ignition tests reported earlier [4] will be summarized here for convenience.

Delayed ignition was obtained by standard exposure of the specimen as in the flame spread test except that the pilot flame was withheld for selected time periods. After forcing ignition by application of the pilot flame, flames travelled down the specimen rapidly to a position determined by the selected delay. The flame was allowed ten seconds to become established and was then extinguished. This permitted determination of the position of the flame front for each selected exposure period. The equivalent blackbody temperature of the panel was pre-set at 670°C as it was during the regular flame spread test. From the calibration of irradiance at each position on the specimen it is possible to obtain the level of irradiance at the leading edge of the char produced by the delayed ignition test. This irradiance-time data was compared with uniform flux data, the latter having been obtained from irradiance-time measurements with pilot ignition of two inch square specimens that were uniformly irradiated.

The delayed ignition data is compared with the uniform flux data for hardboard and balsa wood in figure 1. The denser hardboard material shows good agreement between the uniform flux and delayed ignition data. The less dense balsa wood shows that under delayed ignition, the balsa wood ignites below the critical uniform flux as shown on the right edge of the ordinate scale. The critical flux was obtained from the uniform flux data by plotting irradiance versus the reciprocal ignition time and extrapolating to zero of the reciprocal time scale. The critical flux is the highest irradiation at which ignition would not occur during very long exposures of uniform irradiation in the presence of a small pilot flame.

Considering the delayed ignition of balsa wood, figure 1 shows the time of ignition was twenty seconds for an incident flux only slightly greater than the critical. This corresponds to the energy flux at the nine inch position on the specimen. Early ignition of this point near the critical irradiance is undoubtedly affected by the flow of heat within the material

* $K = 4.65 \times 10^{-4}$ cal/cm^2 sec $\frac{°C}{cm}$, $\rho = .91 \frac{g}{cm^3}$, C = .34 cal/g°C

** $K = 2.9 \times 10^{-4}$ cal/cm^2 sec $\frac{°C}{cm}$, $\rho = .86 \frac{g}{cm^3}$, C = .20 cal/g°C

from regions which are far above the critical value. The data presented for hardboard do not show this effect since the two types of test give very nearly the same results.

A comparison of the same tests on maple, red oak, poplar, and spruce woods show that the observed separation increases with decreasing density. The above order of woods is with decreasing $K\rho C$ but with increasing diffusivity. It appears as if the higher irradiance and heat absorption at the top of the specimen accelerated the release of volatiles appearing at the surface. It is to be expected that this effect would be more pronounced in the less dense materials since lighter materials attain a higher surface temperature for a given irradiance and time of exposure than denser materials. This, coupled with the increased diffusivity of the lighter materials, suggests that conduction of heat along the surface plays an important role in the spread of flame along a surface.

If the application of the pilot flame is withheld beyond the minimum time for the appearance of a flame, it is possible to have a net flow of heat into a given region which would exceed that received directly from the panel. This increased heat will prepare the specimen so that a flame would travel over its surface at a greater rate. In order to show this effect an additional series of delayed ignition flame spread tests were performed.

In this series, the pilot was not applied at the start of the exposure but was again withheld for selected time periods. After a selected delay, ignition was forced at the top. The flame front travelled down the surface very rapidly and after establishing itself, was allowed to continue along the specimen. The time of arrival of the flame front at each three inch position was recorded from visual observations. Position along the specimen was converted into irradiance and the irradiance-time data compared with the uniform flux and regular flame spread data in figure 2.

Figure 2 presents the results of the uniform flux, the delayed ignition flame spread, and regular flame spread tests for the hardboard specimens. The upper curve is the pilot ignition data using uniformly irradiated 2 in. square specimens. This curve approaches the critical value asymptotically with increasing time. The lowest curve is the flame spread data. The delayed ignition flame spread data for delays of 180, 240 and 300 seconds are represented by the curves which separate from the upper curve and approach the lower curve at longer times.

The uniform flux and the regular flame spread curves appear to converge at the higher irradiance levels. At the point corresponding to the appearance of flame during the flame spread test, the curve for the irradiance-time data begins to fall below the data for uniform flux. The separation continues so that after 300 seconds the flame was travelling along surfaces which were receiving less than the critical value of irradiation. The flame continued to the lower end of the specimen where the irradiance was .08 cal/cm^2 sec. From these results, it may be concluded that specimen flaming contributes additional heat input to the unignited portions and results in ignition at sub-critical values of irradiance.

The three delayed-ignition flame spread curves appear to converge with the regular flame spread curve at about 600 seconds. From a position-time plot (not shown) it is evident that the velocity of the flame at each position on the specimen increased with increased delay, emphasizing the importance of the additional heating time. This additional time allowed the material to be heated to a greater depth as well as allowing the surface temperature to more nearly approach the ignition temperature. Both effects speed up the thermal decomposition process and result in increased flame velocity at each position.

The empirical formula developed in reference 4 for the pilot ignition of uniformily irradiated material is

$$(I-I_p)t^n=A. \tag{1}$$

The experimentally determined time of flame arrival at a given position on the regular flame spread specimen corresponds to an irradiance from this formula greater than that which the specimen receives directly from the radiant panel. This difference continues to increase as the flame progresses down the specimen. It can be well represented at any time by

$$\Delta I = Bt^m. \tag{2}$$

where ΔI is the irradiance excess in the presence of a flame, i.e., the difference between that required for ignition under uniform flux conditions and that incident at a point on a flame-spread specimen at the corresponding time. The value of B for each material is related to thermal diffusivity as follows,

$$B = 24.4\alpha - 3.56 \times 10^{-2} \tag{3}$$

when α is in cgs units. No simple expression for m as a function of the physical and thermal properties was found, and it was considered constant with a value of 0.71. This is the average value of m for hardboard, maple, red oak, spruce, and balsa woods where the individual values ranged from 0.59 for balsa to 0.97 for hardboard.

Using the above expression for ΔI it is possible to represent the flame spread data by

$$(I+\Delta I-I_p)\ t^n = A, \tag{4}$$

and the constants I_p, n, and A by the following:

$$\begin{aligned} I_p &= 4.24 \times 10^{-1} - 8.75 \times 10^{-4}\ (K\rho C \times 10^6) \\ m &= 9.75 \times 10^{-1} - 1.20 \times 10^{-3}\ (K\rho C \times 10^6) \\ A &= K\rho C[6.90 \times 10^2 - 3.15 \times 10^4\ (K\rho C)^{\frac{1}{2}}]^2 . \end{aligned} \tag{5}$$

It was found that at any time after delayed ignition, except for very long times, ΔI at a given position along the specimen varied inversely with the delay. If we consider that the temperature of the flame is constant this again indicates that the increased exposure has prepared the surface so that the flame itself need supply less energy and can therefore proceed at a greater rate.

3.2 Reduced Irradiance Tests

The uniform flux data asymptotically approach the critical value while the flame spread data continue to much lower irradiance levels at a decreasing rate. Attempts were made to determine if a minimum critical flux exists for surface ignition during the non-uniform irradiation of the flame-spread test. To do this, radiant panel blackbody temperature specimens were tested as in the regular flame spread test except for a reduced radiant input (by operating the radiant panel at a blackbody temperature of 487°C) and it was found that the flame continued to travel in regions where the flux was as low as .04 cal/cm^2sec. However, it was also observed that a flame will not spread beyond the area of the igniting pilot in the complete absence of additional irradiation. Other tests have shown that flames will not continue to travel along the surface if the specimen is shielded from the radiating panel during the course of a regular flame spread test. In the latter case the flame travel stopped and all flaming ceased within a few minutes.

It is not likely that a critical irradiance level less than .04 cal/cm^2sec is realistic. This value was the measured flux input at the lower end of the specimen during a reduced irradiance flame spread test and hence was a measure of the incident radiant flux at the surface at the start of a test only. It does not consider the effect of increased panel temperature due to the presence of a flaming specimen.

In order to determine the effect that re-radiation from a flaming specimen could have upon the radiant panel temperature, a few tests were performed while the center portion of the panel was monitored by an auxiliary radiometer. (The radiometer used to measure and control the panel temperature prior to the start of a test does not permit viewing the panel during the test.) In this series of tests the control radiometer was used to set the panel at an effective blackbody temperature of 487°C. Two tests were performed while monitoring the panel temperature: a reduced intensity flame-spread test and a thirty-seven minute delayed-ignition, reduced intensity test. The results are shown in figure 3 in terms of the uncalibrated millivolt output versus time. The broken line shows flame position versus time during the reduced intensity flame spread test. It can be seen that re-radiation from the flaming specimen increases the panel temperature considerably more than the presence of a non-flaming body (whose surface temperature is increasing). It should be noted that both specimens caused a slight increase in the radiometer output as soon as they were placed in test position. This is attributed to the reflection of the incident radiation from the specimen surface and not to an increased panel temperature since the thermal inertia of the radiant panel is appreciable. It is also likely that some portion of the output of the radiometer during the flaming tests was due to reflection from the specimen and not all due to increasing panel temperature.

Panel temperature was not monitored during the regular flame spread test. The control radiometer at the start of each test had an output of 1.95 millivolts corresponding to a blackbody temperature of 670°C. After a ten minute flame spread test, the output was found to be 2.05 millivolts corresponding to 680°C. At this time the flaming specimen had been removed so that reflections from the specimen were absent. Additional measurements using calibrated radiometers during flame-spread tests should enable more quantitative estimates of this effect to be made.

3.3 Variable Thickness Tests

To determine the effects of thickness upon flame spread, specimens were prepared from 1/4-inch thick tempered hardboard in the following uniform thicknesses; .070, .145, .25, .50 and 1.00 inches. The thin specimens were prepared by sanding the 1/4-inch material while the thick specimens were made up of layers of the 1/4-inch stock and held together with a wood glue. All except the one-inch thick specimens were backed with half-inch thick asbestos millboard.

The specimens were all exposed to the regular flame spread test and the results are shown in figure 4 in terms of the time of flame arrival and the corresponding irradiance at the position of the flame. The thinnest specimens (.070 in.) ignited earliest and the flame travelled at a greater rate over the top twelve inches than it did for all other thicknesses. For a specimen twice as thick (.145 in.) the primary ignition took longer and the flame did not spread as fast. In both tests the flame appeared earlier and spread faster than during the standard test with the .25-inch thick specimen.

Flame spread tests performed with .50 and 1.00 inch thick specimens showed the same trend but were only slightly different from the standard thickness specimen. It appears as if specimens of .25 in. thickness or greater all give very nearly the same flame spread factor when tested in the standard manner. This is not the case when thicknesses below the standard thickness are tested.

A series of regular flame spread tests were performed on hardboard specimens which had horizontal grooves (i.e., parallel to the specimen width) on either the exposed or unexposed surfaces. The grooves were saw cuts 1/16 of an inch wide and 3/16 of an inch deep in 1/4 inch thick specimens. When the cuts were on the unexposed surface, no measurable differences from the regular flame spread test were observed. This suggests that conduction effects are unimportant beyond 1/16 of an inch from the surface.

Specimens tested with the saw cuts on the exposed surface gave temporary differences. The flame arrived at the edge of the saw cut at the usual time, but was then delayed for a longer time than it would normally take for the flame to travel 1/16 inch. After jumping the gap, the velocity of the flame increased slightly so that it arrived at the next saw cut again at the usual time. The same effect to a lesser degree was noticed in the delayed ignition flame spread test when specimens were tested with horizontal grooves on the exposed surface.

3.4 Surface Temperatures

Surface temperatures have been measured during the standard flame spread test and compared with those measured on a specimen where pilot ignition was delayed. Approximate surface temperatures were measured using a series

of stripes of temperature-indicating paints placed at each three-inch position along the specimen. Upon reaching the specified temperature the paint underwent a prescribed color change and the time of this change was recorded from visual observations. The manufacturer claims the paints to be accurate to within 1% and when applied in thin coats the time lag is reported to be a small fraction of a second.

Figure 5 presents the positions of the 300°F, 400°F, 500°F, and 600°F temperature fronts as they traveled down the specimen. It also shows the flame front as it traveled along the specimen in a standard flame spread test. These measurements indicate that a temperature of 600°F was reached at the three-inch position prior to the arrival of the flame. The 600°F front also reached the six-inch position just shortly before the flame and it appears as if the flame front starts to lead the measurable 600°F front soon afterwards. After this time, the 600°F paint did not change color until it was actually touched by the flame. At the twelve-inch position the flame and the 500°F front approached at about the same time and by the time the flame reached the fifteen inch position it was very close to overtaking the 400°F front. After this time the 400°F, 500°F, and 600°F paints were unchanged until touched by the flame front.

A comparison of temperature fronts during a 600-sec delayed ignition test shows, figure 5, that these were very similar except when the flame approached a given temperature front. In this case the apparent velocity of the temperature front increased when the flame approached indicating that the effect of the flame was restricted to the immediate neighborhood of the flame front.

Approximate surface temperatures were also measured on some specimens in the complete absence of flaming to investigate the effects of longitudinal conduction. Specimens included those with horizontal grooves previously described and short-length specimens centered at the nine-inch position with the remainder of the test area consisting of asbestos millboard. In all, five types of specimens were tested using temperature indicating paints without flames. They were:

a - 6 by 1 inch specimens
b - 6 by 3 inch specimens
c - 6 by 18 inch specimens
d - 6 by 18 inch specimens with 1/8 inch deep saw cuts each inch along the unexposed surface
e - 6 by 18 inch specimens with 3/16 inch deep saw cuts each inch along unexposed surface

For all specimens, the time for attainment of each of several surface temperatures at each position was noted. Temperature indications were obtained from 300°F to 600°F in 50°F and 100°F steps and are shown in

figure 6 for the 9-in. positon. The greatest difference noted, 30 sec, was for the 600°F surface temperature reached on the one inch long specimen in 210 seconds and on the three inch long specimen in 240 seconds. Although measured times from repeat tests were generally within 15 seconds, there was no apparent correlation with longitudinal conduction. These results indicate that conduction along the surface without a flame is not significant for this material. Due to the increased flame spread of balsa wood and the resulting short ignition times, temperature measurement was not attempted until reduced irradiance tests could be performed satisfactorily. It is thought however that conduction in less dense materials will be more pronounced and surface temperatures will be greater for a given exposure on the longer specimens.

It was reported earlier [6] that surface temperatures could be calculated at the time of ignition. From all the irradiance-time data obtained experimentally for each material the method gave reasonably constant surface temperatures at the time of ignition. Correlation on this basis has also been shown by Simms [5]. Since the hardboard in the present report is slightly less dense than that reported previously [4], use was made of the relation between surface temperature at the time of ignition and thermal inertia, $K\rho C$, namely

$$T_{ign}(°K) = 667 - .527\ (K\rho C \times 10^6). \qquad (6)$$

This equation was based upon an assumed natural convection heat transfer coefficient of 4.7×10^{-5} cal/cm^{2}sec °C. For a

$$K\rho C \text{ of } 144\times10^{-6}\ \text{cal}^2/\text{cm}^4\ \text{sec}\ (°C)^2,$$

$$T_{ign} = 591°K = 604°F.$$

This compares favorably with the surface temperatures measured with the temperature-indicating paints.

Previous work (4) showed that pilot ignition occurs when the surface reaches a given temperature. Actually it was shown that the calculated temperature for ignition decreased slightly as the irradiance was decreased. However, the time of ignition increases as the irradiance is decreased and this permits the temperature front to penetrate farther into the material so that the surface temperature requirement may be relaxed slightly.

It can also be shown that surface temperatures in excess of 610°F may not result in ignition if the time is excessively long. The uniform flux test gave the critical irradiance for pilot ignition of hardboard as .30 cal/cm^{2}sec. Although this irradiance may give a maximum surface temperature of 710°F, ignition did not occur at this irradiance level. Since the supply of volatiles is exhaustable, time becomes an important factor.

In such cases, it appears as if this effect might be explained by considering the rate of volatile generation as suggested by Bamford, Crank, and Malan (4). From this work, it was considered that a minimum rate of volatile generation was necessary in order for a sustained flame to exist on the surface of combustible materials.

In order to check the compatibility of a minimum surface temperature and a minimum rate of volatile generation for the spread of flames, it was necessary to determine the effect of the flame itself. So far, it has been established that conduction in the solid is not significant in the absence of a flame and that, in the presence of a flame, conduction is restricted to the immediate neighborhood of the flame front and to a thin surface layer not greater than 1/16 inch thick. Furthermore, an ignition criterion based on the attainment of a critical surface temperature is in good agreement with surface temperature measurements. However, even if the critical surface temperature is exceeded, lengthy irradiation at flux levels just above critical may not result in ignition because of excessive volatile depletion.

3.5 Numerical Solution: Sub-surface Conduction

To determine to what extent sub-surface conduction in the solid could contribute to flame propagation, numerical solutions were sought for the temperature distribution in the immediate vicinity of the flame front. The analytical solution to the problem of a surface of a semi-infinite combustible material originally at room temperature and receiving radiant energy as a function of position along the surface $y=0$ and which loses heat through convection and radiation is further complicated by the presence of the flame which moves at a nonuniform rate along the surface.

The model chosen as a first approximation in the numerical solution was a semi-infinite slab initially at uniform temperature throughout with a step temperature input applied over a portion of its surface at $t=0$ while the remainder of the surface was considered impervious to the flow of heat, i.e. perfectly insulated. To represent conditions at the moment of flame arrival, the measured surface temperature at a given position along the specimen was taken as the initial temperature and the surface temperature of the portion covered by the flame was assumed to be 1400°F.

A two dimensional numerical solution was obtained for the above model (see appendix) with initial temperatures of 590°F, 540°F, 480°F, 405°F, and 345°F, representing the 6, 9, 12, 15, and 16.5 inch positions respectively on the flame spread specimen at the time the flame reached each position. Since earlier work with uniform flux input had shown the surface temperature to be 610°F at the time of pilot ignition of hardboard,

this temperature was considered to be critical in the spread of the flame. The velocity of the 610°F front along the surface was determined for a given initial temperature and the time at which this velocity equaled the measured flame velocity was determined. The position of the 610°F front both along the surface and in depth was obtained at the time of equal velocities.

The results of the numerical solution presented in the appendix are given in Table 1.

Table 1. Results of the numerical solution obtained by equating the velocities of the 610°F front and the flame.

Position (in.)	I cal/cm^{2}sec	v_f cm/sec	t (sec)	T_o (°F)	x_a (cm)	y_a (cm)	R g/cm^{2}sec
9	.420	.115	175	540	.020	.025	.133φ
12	.300	.049	300	480	.028	.033	.053φ
15	.195	.026	500	405	.033	.041	.030φ
16.5	.130	.018	675	345	.037	.047	.022φ

where

I is the irradiance on the specimen,
v_f is the velocity of the flame front,
t is the time of flame arrival,
T_o is the initial (measured) temperature at the time of flame arrival,
x_a is the position along the surface of the 610°F front at the time of equal velocity,
y_a is the depth of the 610°F front at the time of equal velocity,
R is the rate of volatile generation given by

$$R = \varphi\rho \frac{y_a v_f}{x_a} \qquad (7)$$

with φ the fraction of mass converted into volatiles at the time of the appearance of the flame. φ was considered constant since the position of a constant front was investigated.

The work of reference 6 concluded that in order for a sustained flame to exist on the surface of a material a minimum rate of volatile generation was necessary. This minimum value was stated to be 2.5×10^{-4} g/cm^{2}sec. It follows that a sustained flame on the surface will travel as soon as this minimum rate of volatile generation is established in the area ahead of the flame front. The results of Table 1 showed that φ was not constant but that it varied with irradiance and ignition time. It also showed that the minimum rate of volatile generation was not the criterion where the irradiance was greater than the critical value.

The attainment of a minimum surface temperature appears to be the criterion where the irradiance is above the critical value. The time required for the velocity of the temperature front to equal the flame velocity must be the controlling factor. This criterion could also be applied to irradiance levels below critical when modified by the time required to attain equal velocity.

In order to investigate both criteria in the range of the critical value of irradiance, a more refined numerical solution than that attempted here is required. Additional flame-spread tests and surface temperature measurements at reduced incident flux would also be useful.

4. SUMMARY

Uniform flux and delayed ignition tests gave very nearly the same irradiance-time results for cellulosic materials which have a high thermal inertia, $K\rho C$. As the thermal inertia was reduced, with a corresponding increase in thermal diffusivity, more pronounced separation of the data was observed. In the delayed ignition tests on materials of low thermal inertia, pre-flaming thermal conduction in the solid allows heat to flow from positions of high irradiance to those of low irradiance so that the total heat flow into a given volume at the surface is larger than the direct incident irradiation. It is suggested that this effect is the reason that uniform flux data and standard flame spread data separate. This effect would be more pronounced in the neighborhood of the flame front due to the increased temperature of the flame. This accounts for the spread of flames at incident flux levels which are below the critical value.

The delayed ignition flame-spread tests have shown that flame velocity is increased at each position according to the delay chosen so that the flame arrives at the 15-inch position at the same time for delays of 180, 240, and 300 seconds. In the case of hardboard, Figure 1 showed the effect of pre-flaming conduction to be negligible. The increased flame velocity during a delayed ignition flame spread test compared to a standard flame spread test shows the significance of the pre-heating period. This allows the surface to attain a slightly higher temperature prior to the application of the pilot as well as allowing the material to be heated to a greater depth. More volatiles are generated and the time required for the flame to accomplish its mission is reduced thereby increasing flame velocity.

Surface temperatures were measured during the standard flame spread and delayed ignition flame spread tests. Results showed that the effect of the flame is limited to a small area in the vicinity of the flame front. Measured surface temperatures compared well with those calculated for the case of the uniform flux tests. For hardboard, ignition occurred when the surface temperature was approximately 610°F. Measured temperatures were found to be slightly greater than 600°F when the flame passed a test point.

An attempt was made to show the possible compatibility of two criteria for ignition, i.e., attainment of a minimum surface temperature and the generation of a minimum rate of volatilization. In determining the minimum rate of volatilization, it was assumed that, at the time of ignition, all specimens were converting the same fraction of their mass into volatiles. The results show that if the flame spreads as soon as a minimum rate of volatiles is present, then the assumed constant is a function of intensity and total time of exposure. However, if the assumed constant is a constant, then the minimum rate of volatile generation criterion is not valid. This could be checked by a series of tests similar to the uniform flux tests with the addition of thermogravimetric analysis.

Weight loss measurements on specimens which were receiving a uniform flux could take into account both criteria. The method outlined using the numerical solution could then determine which criterion was governing the spread of flames.

If the attainment of a certain temperature on the surface is the governing criterion, then the time required for the velocity of the temperature front to equal the flame velocity would be important in determining when a flame would cease to travel. This could be accomplished with a more refined numerical analysis and with additional surface temperature measurements at irradiance levels below the critical value.

5. REFERENCES

1) "Method of Test for Surface Burning Characteristics of Building Materials" ASTM E84-61, 1961 Book of ASTM Standards.

2) Robertson, A. F., Gross, D., Loftus, J. J., A Method for Measuring Surface Flammability of Materials Using a Radiant Energy Source. PROC. ASTM Vol. 56, pp 1437-53, 1956.

3) Proposed Method of Test for Surface Flammability of Building Materials Using an 8-Foot Tunnel Furnace, PROC. ASTM Vol. 60, pp 462-7 (1960).

4) Buschman, A. J., Ignition of Some Woods Exposed to Low Level Thermal Radiation. NBS Report 7306, 1961.

5) Simms, D. L. "Ignition of Cellulosic Materials by Radiation", Combustion and Flame, 4, pp 293-300, Dec. 1960

6) Bamford, C. H., Crank, J., and Malan, D. H., The Combustion of Wood, Part I, PROC. Cambridge Phil Soc., Vol. 42, pp 166-182, Oct. 1945.

6. SYMBOLS

A, B	Constants depending upon material.
C	Specific heat, cal/g°C.
I	Irradiance (or flux), $cal/cm^2 sec$.
I_p	Critical irradiance (or flux), $cal/cm^2 sec$.
ΔI	Irradiance excess in the presence of a flame, $cal/cm^2 sec$.
K	Thermal conductivity, $cal/cm^2 sec \frac{°C}{cm}$.
M	Weighting modulus in numerical computation.
m, n	Constants depending upon material
N_l	Ratio of flame velocity and the temperature front velocity.
R	Rate of volatile generation per unit surface area, $g/sec\ cm^2$
T	Temperature.
t	Time, seconds.
v	Velocity, cm/sec.
W	Width for numerical computation, cm.
α	Thermal diffusivity, cm^2/sec.
Δx, Δy	Space increments in numerical computation, cm.
Δt	Time increment in numerical computation, cm.
φ	Fraction of mass volatilized at the time of flame arrival.
ρ	Density, g/cm^3.
θ	Temperature rise.

Subscripts

a	At the time when the flame velocity equals the velocity of the temperature front.
ave	Average value.
ign	At the time of ignition.
f	Flame.
o	Initial.

7. APPENDIX

Several attempts were made to study the spread of flames along a surface analytically. In each case the most realistic models were too complex and simplifying assumptions had to be employed. The model chosen was a semi-infinite slab with a step temperature input over a portion of its surface while the remainder of the surface was considered to be impervious to the flow of heat. Numerical solutions were obtained to determine the temperature distribution in the vicinity of the leading edge of the step input. The numerical solution employed a square-grid network, Figure 7a. The initial temperature of the slab was constant but was changed according to the specimen position, each of which was analyzed separately. For this reason temperature rise is considered instead of temperature.

The initial temperature at each position was considered to be equal to that determined experimentally through the use of temperature indicating paints. At time t=0 a portion of the model surface is raised to 1400°F and held at this temperature for the duration of the calculations. A general solution has been obtained in terms of T_0 for ten time intervals.

By using the square network, the temperature rise during a time interval is given by

$$\theta_{o,\Delta t} = \frac{\theta_1 + \theta_2 + \theta_3 + \theta_4 + (M-4)\,\theta_o}{M} \tag{A1}$$

where $M = (\Delta x)^2/\alpha\Delta t$

- Δx is the space interval
- Δt is the time interval
- α is the thermal diffusivity
- $\theta_{o,\Delta t}$ is the temperature of the center point (θo) after the time interval Δt
- θm is the temperature above the initial at the start of a time interval.

The temperature distribution throughout the specimen was determined at each time interval for a total of ten time intervals. Figure 7b presents the temperature distribution along the surface, y=0, in 2 Δt intervals for T_0=345°F corresponding to the 16.5 inch position. In this way the position of the 610°F front can be determined at each time interval. The position of the 610°F front at each time interval presented in figure 7b can be plotted and the velocity of the front determined at each time interval. The results of this intermediate plot are shown in figure 7c.

The velocity of the flame front had been determined for the standard flame spread test at each position. It is now possible to match the flame velocity at the 16.5 inch position with the 610°F front and determine the time at which they are equal.

Arbitrarily assign a value to the time interval and determine the corresponding value of the space interval for M=4. By trial and error, adjust the time interval to a value which will allow N from figure 7c to be in the range of 6 to 10 Δt. Then from figure 7c determine the time at which the velocities are equal. Figure 7c will give this time in terms of the time interval but this is known from the trial and error procedure.

Divide the time found above into ten time intervals and determine the corresponding space interval. With these time and space intervals it is possible with figure 7d to determine the depth of the 610°F temperature front at the time of equal velocities. Figure 7d is a graph of the position below the surface of the 610°F front as a function of the time interval. The same type of graph was prepared in order to obtain figure 7c from figure 7b. The position of the 610°F front at the time of equal velocities along the surface and in depth will be designated x_a and y_a respectively.

At the time of equal velocities the volumetric rate at which material is heated above 610°F is taken as

$$W y_a v_f \tag{A2}$$

The mass above 610°F per unit time is $\rho W y_a v_f$

while the surface above 610°F at this time is $W x_a$.

Therefore, the mass per unit time per unit surface area is

$$\frac{\rho y_a v_f}{x_a} \tag{A3}$$

The rate of volatile generation per unit surface area will be

$$R = \varphi \frac{\rho y_a v_f}{x_a} \tag{A4}$$

where φ is an assumed constant representing the fraction of mass converted into volatiles at the time of flame arrival. The results of the above procedure are given in table 1.

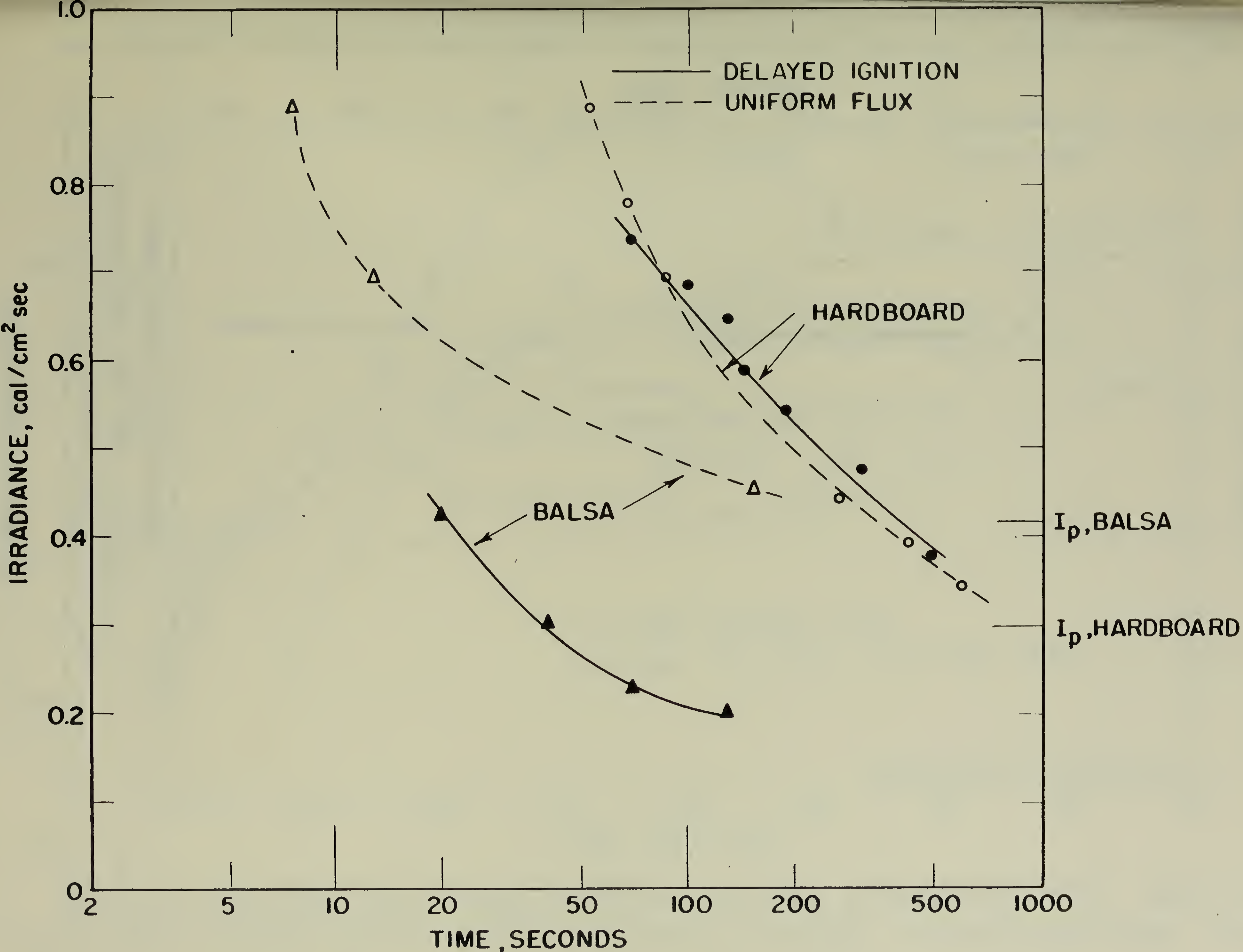


FIG.1 - COMPARISON OF UNIFORM FLUX AND DELAYED IGNITION TESTS ON HARDBOARD AND BALSA WOOD

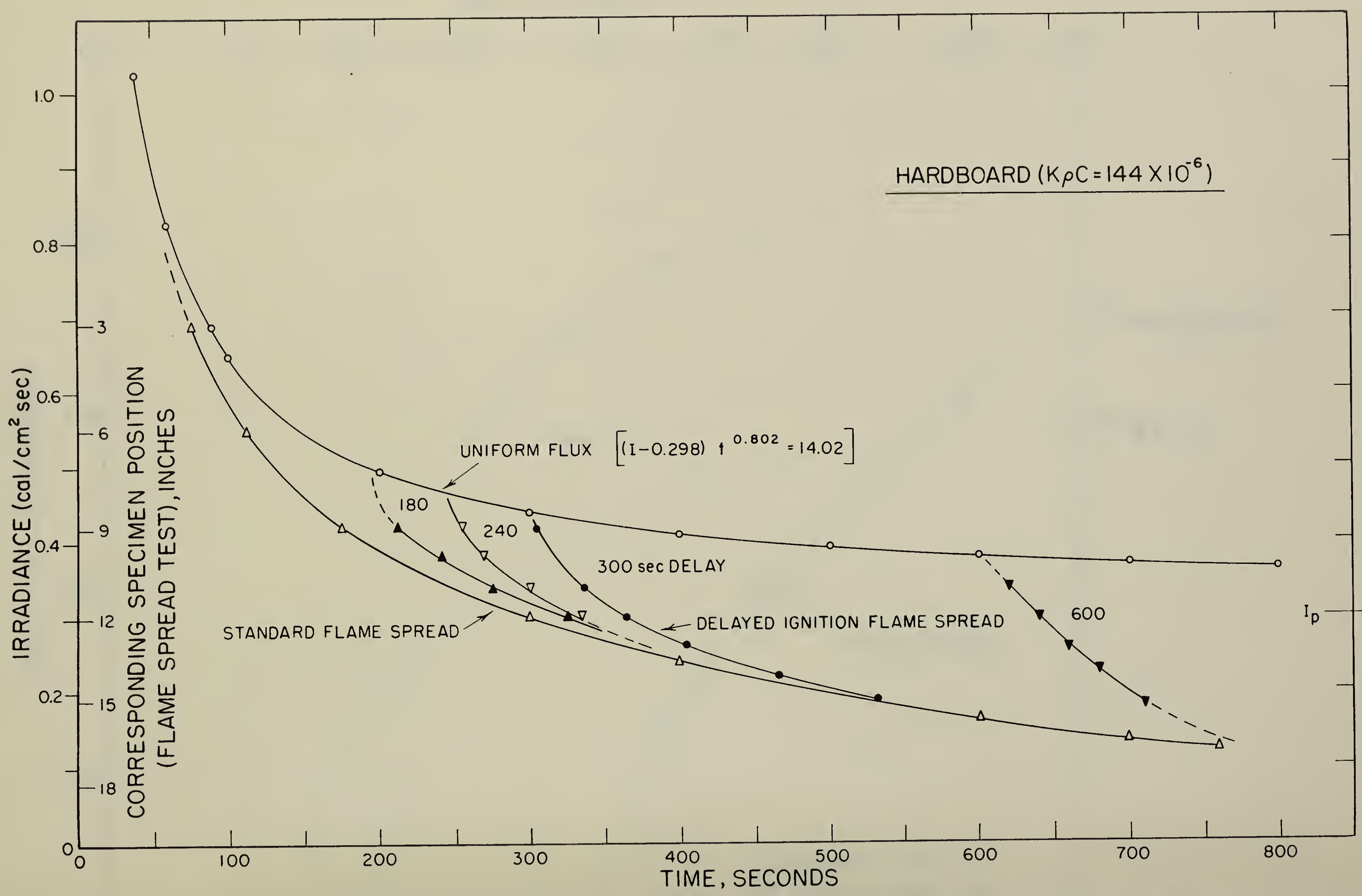


FIG. 2- RESULTS OF UNIFORM FLUX, STANDARD FLAME SPREAD, AND DELAYED IGNITION FLAME SPREAD TESTS

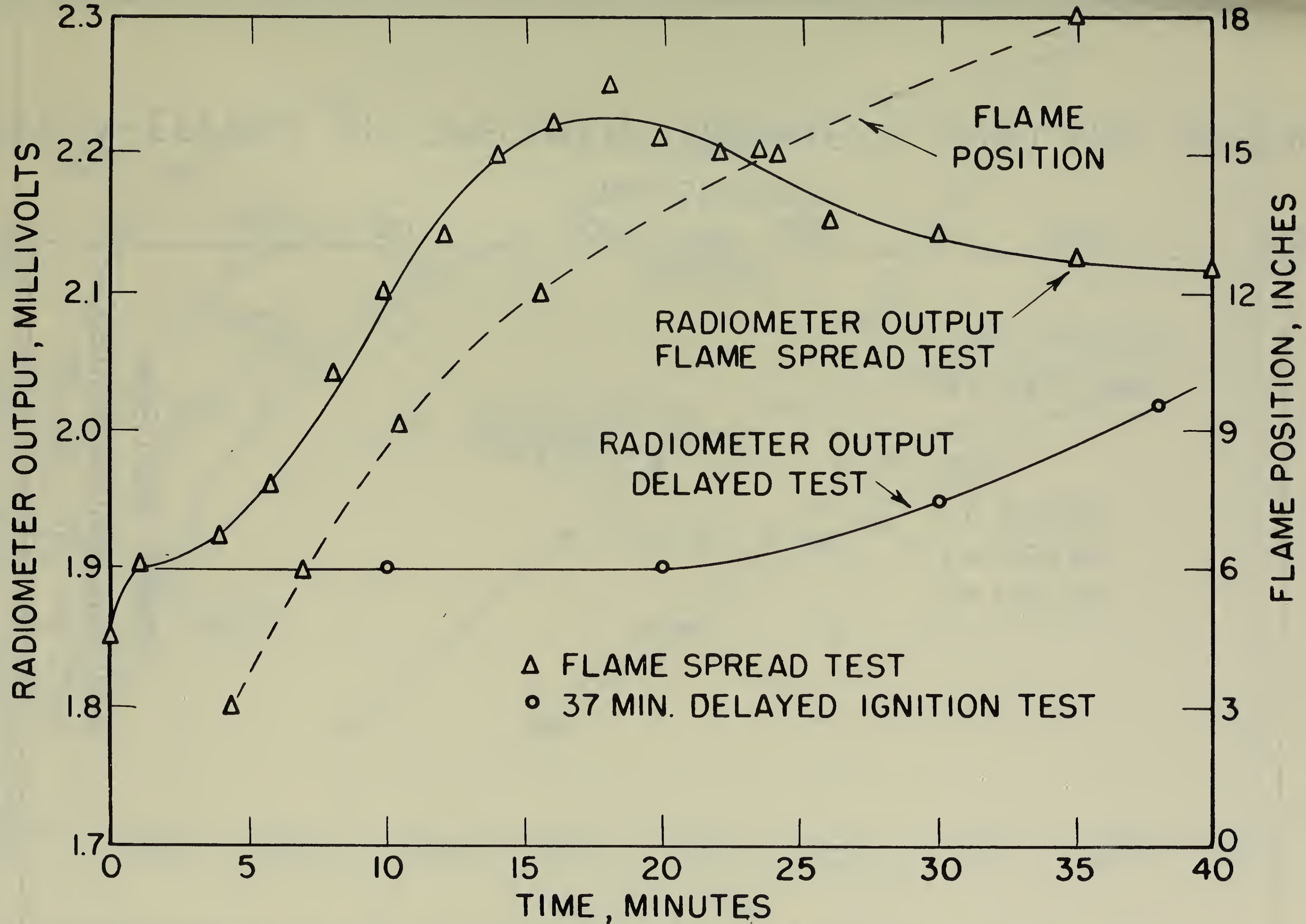


FIG. 3-OUTPUT OF PANEL-MONITORING RADIOMETER DURING REDUCED INTENSITY TESTS (INITIAL PANEL TEMPERATURE, 487°C)

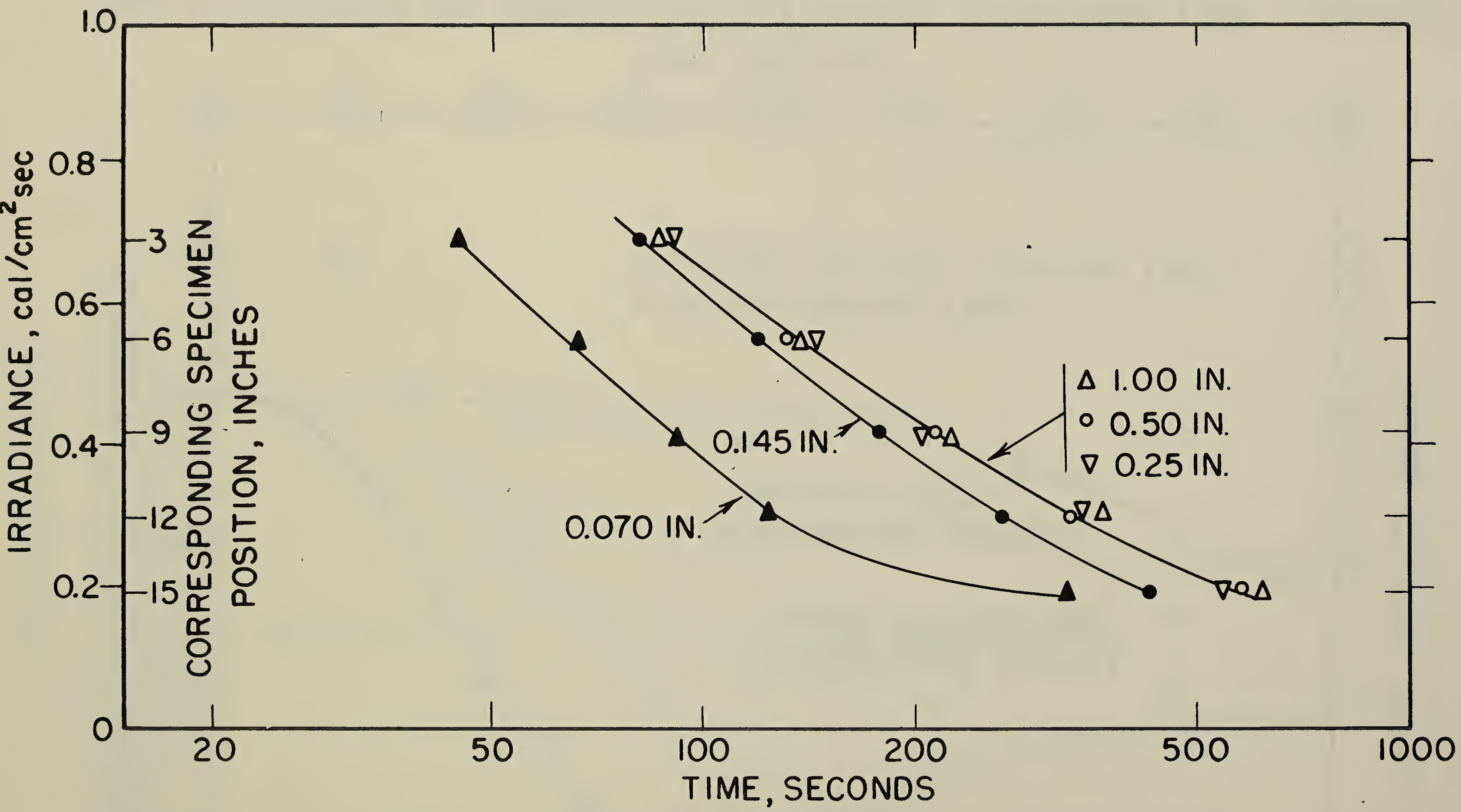


FIG.4-EFFECT OF SPECIMEN THICKNESS ON FLAME SPREAD

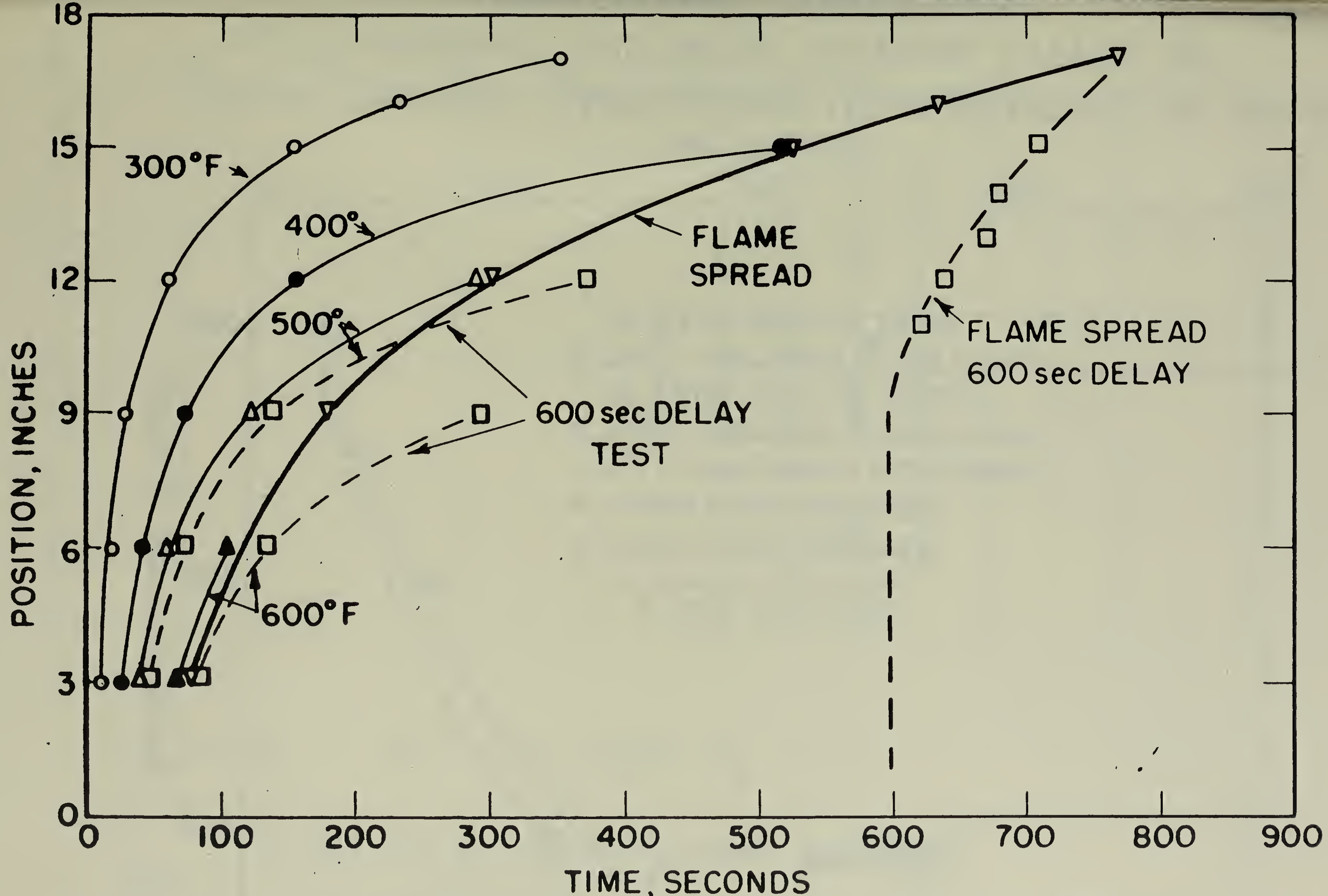


FIG.5 - POSITIONS OF SURFACE TEMPERATURE FRONTS ON HARDBOARD DURING REGULAR AND DELAYED-IGNITION FLAME SPREAD TESTS

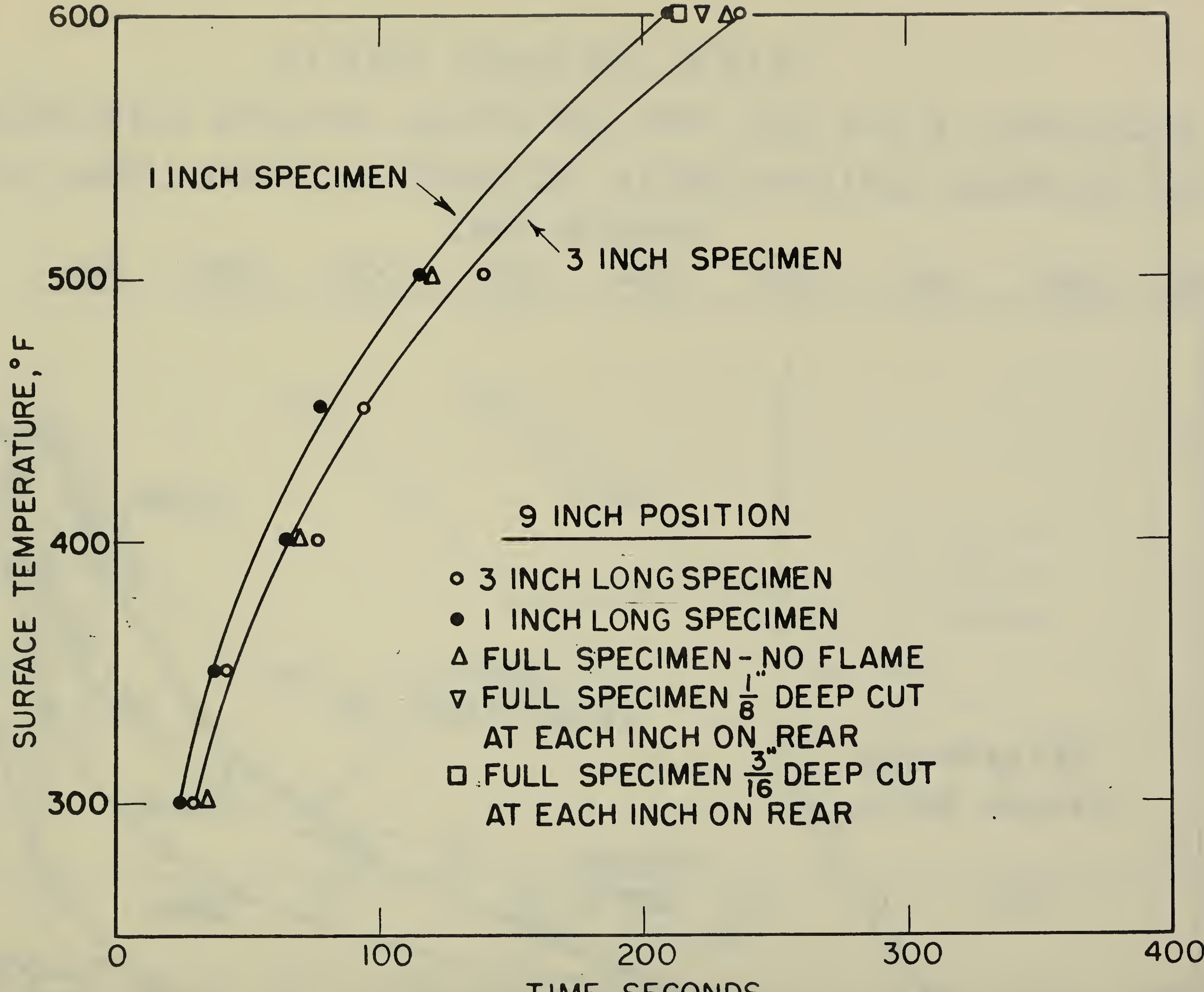
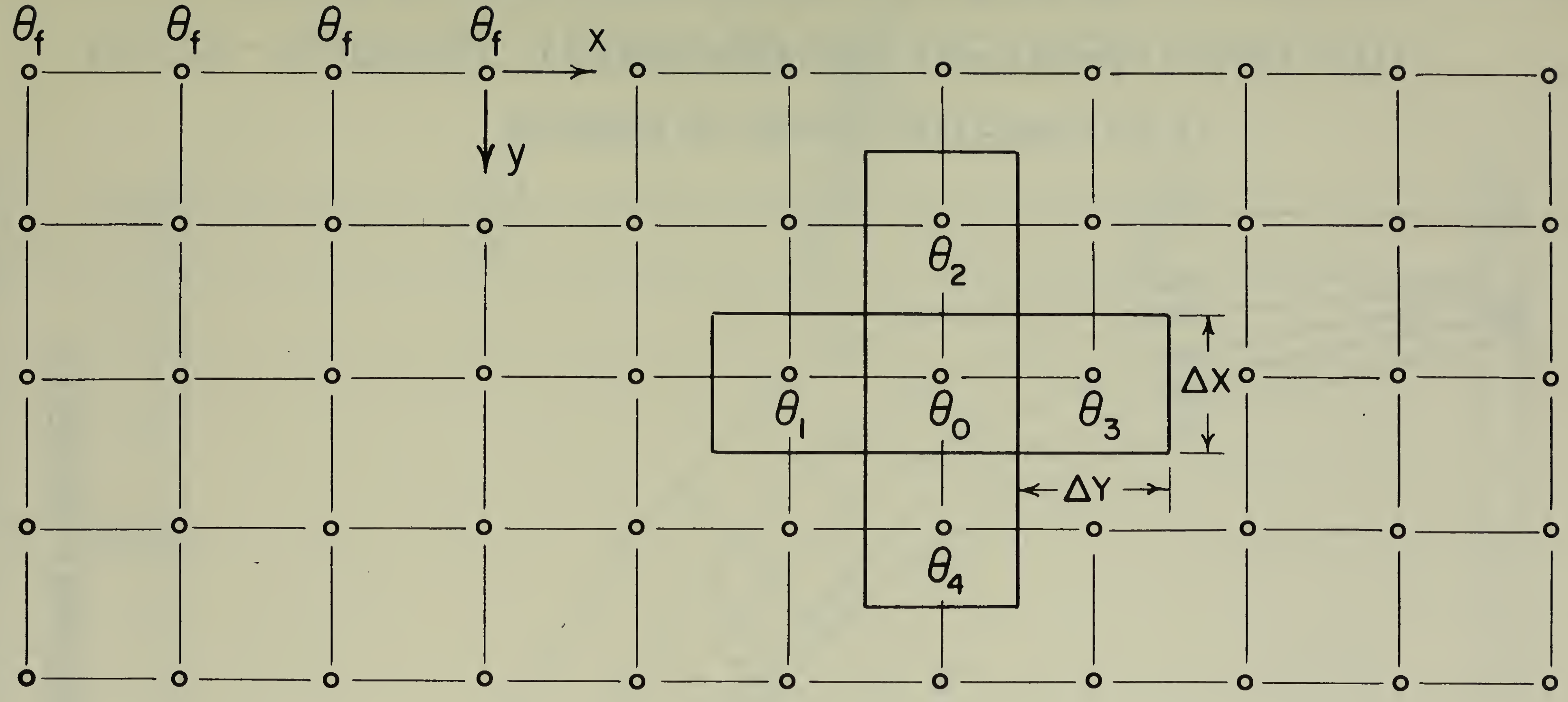


FIG.6 - SURFACE TEMPERATURE MEASUREMENTS ON VARIOUS SIZE HARDBOARD SPECIMENS SHOWING EFFECT OF LONGITUDINAL CONDUCTION



$$\theta_n = T_n - T_o \qquad \theta_f = T_f - T_o = 1400 - T_o$$

$$\theta_{o,\Delta t} = \frac{\theta_1 + \theta_2 + \theta_3 + \theta_4 + (M-4)\theta_o}{M} \qquad M = \frac{(\Delta x)^2}{\alpha \Delta t}$$

FIG. 7a - GRID NETWORK FOR NUMERICAL COMPUTATIONS

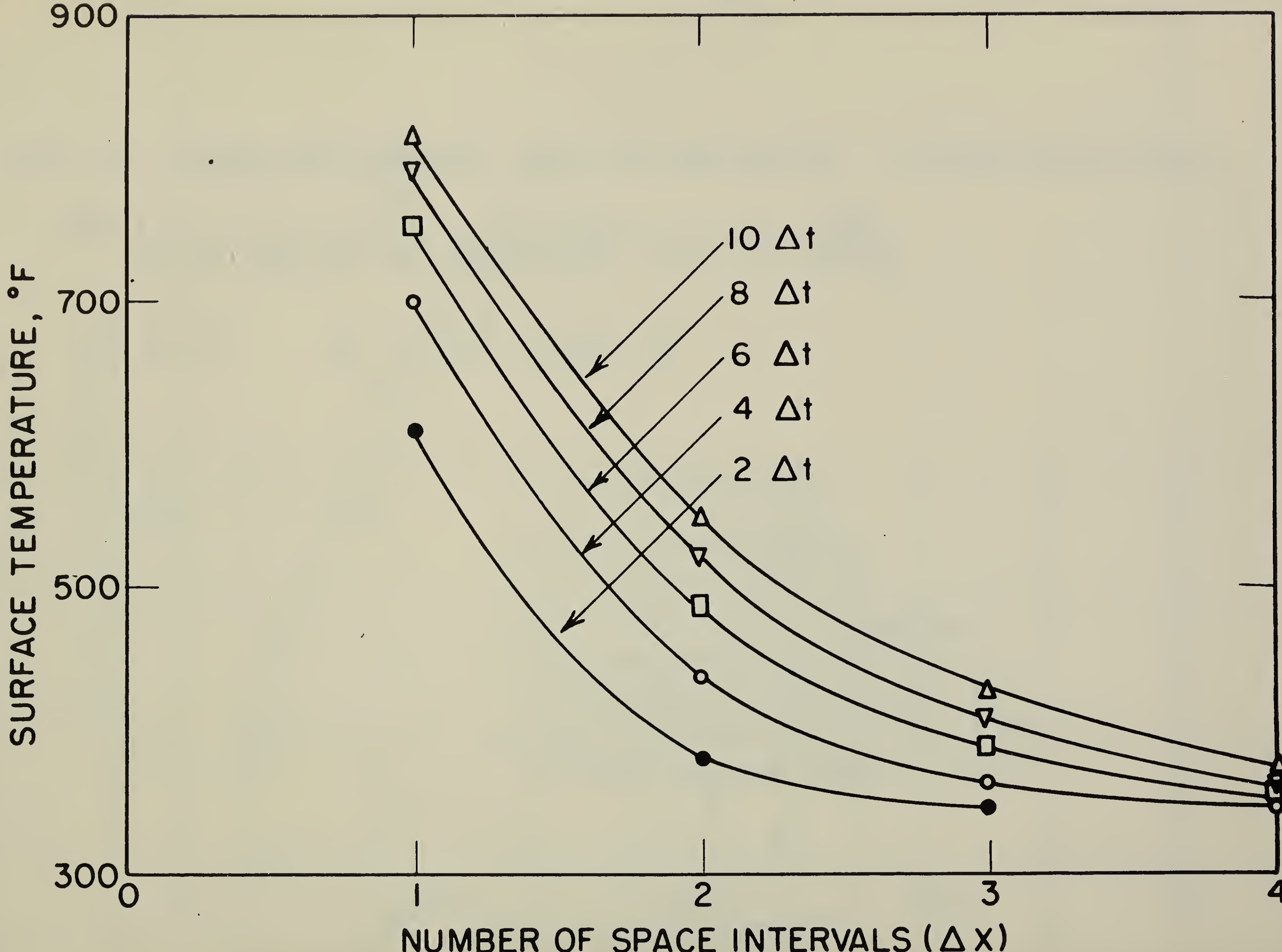


FIG.7b – SURFACE TEMPERATURE DISTRIBUTION (y=0)
AT 16.5 INCH POSITION $T_o = 345°F$

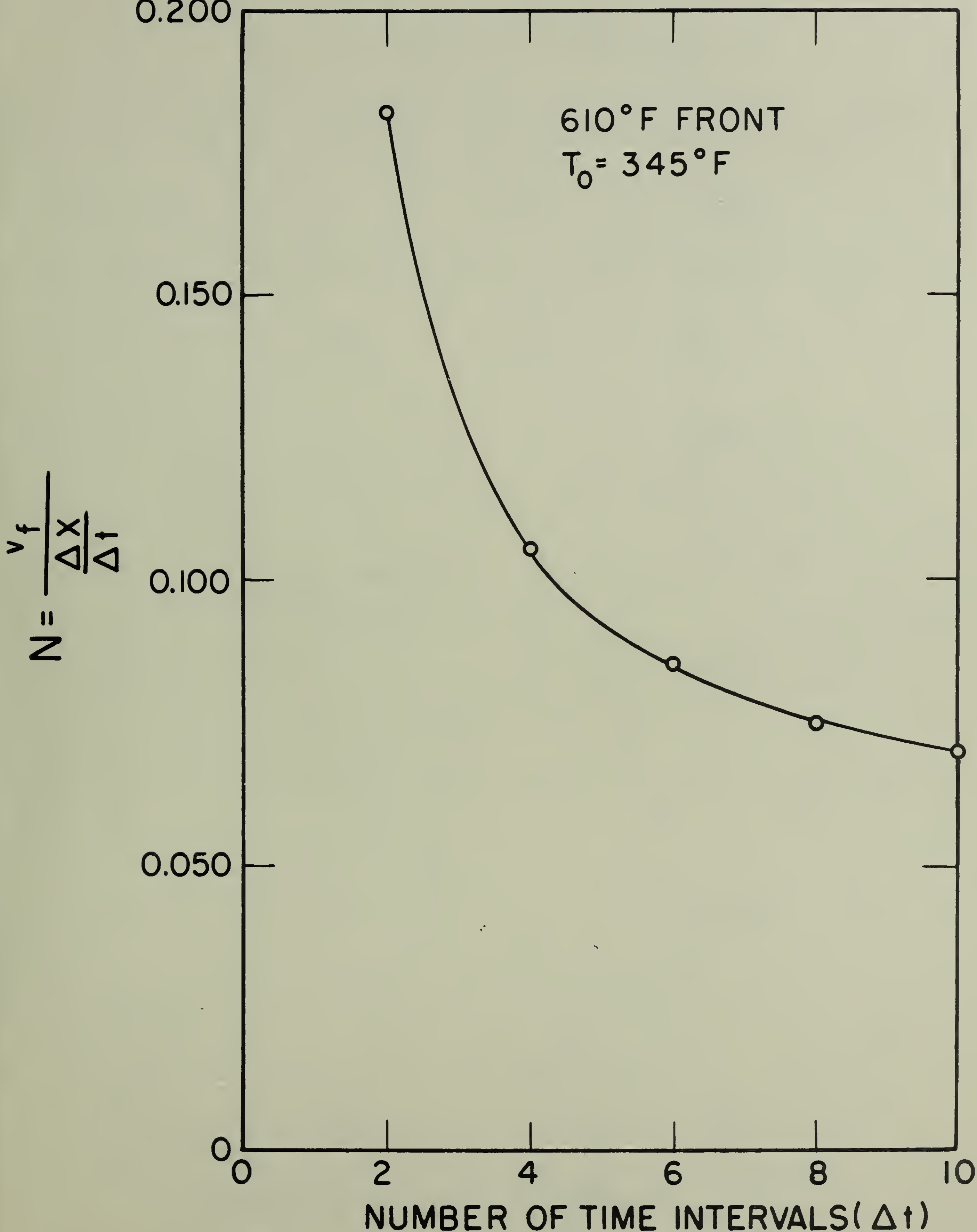


FIG. 7c – VELOCITY RATIO($\frac{v_f}{\frac{\Delta X}{\Delta t}}$) AS A

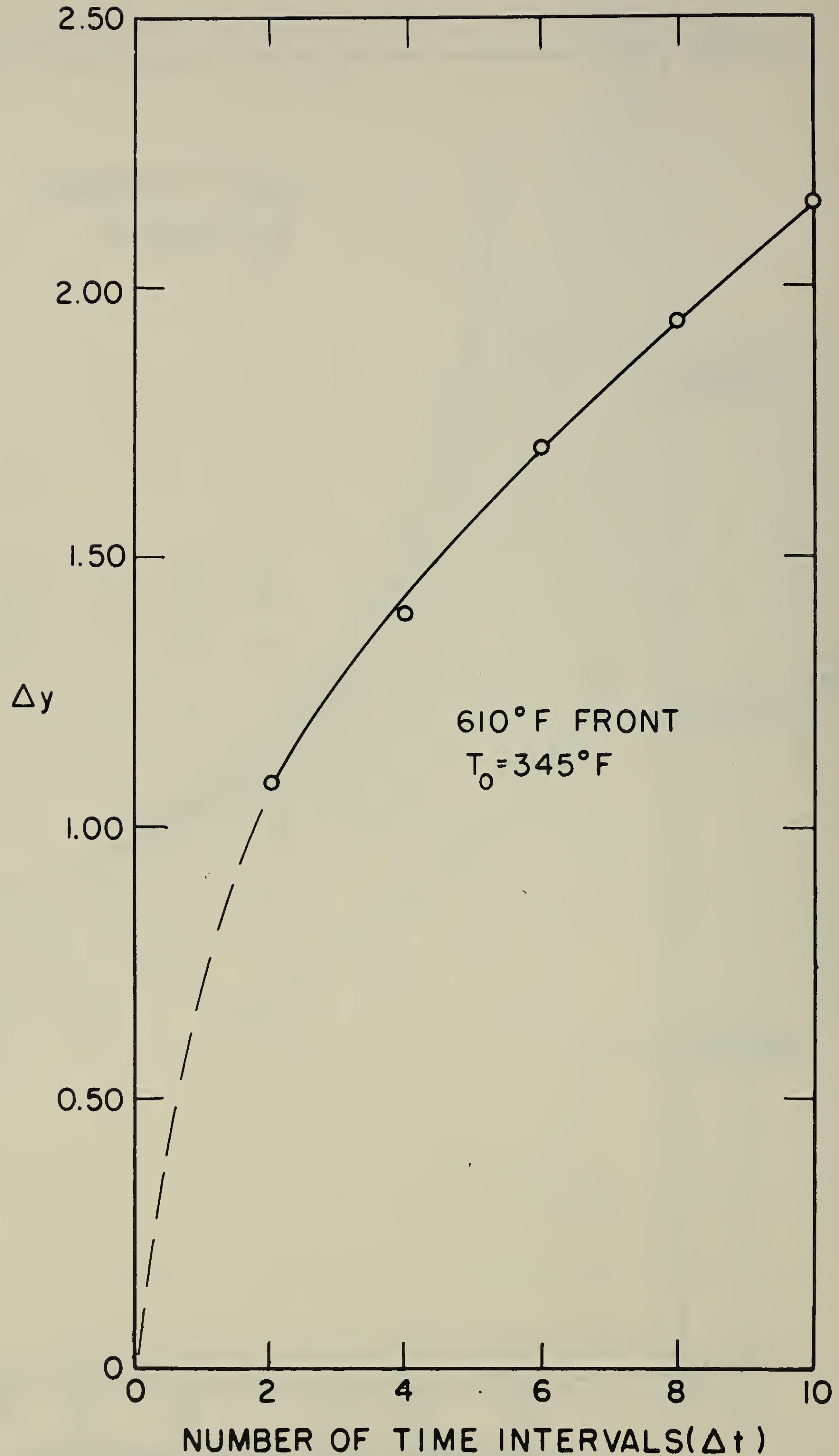


FIG. 7d - POSITION OF 610°F FRONT IN DEPTH

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D. C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage. Absolute Electrical Measurements.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Volume.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

CRYOGENIC ENGINEERING LABORATORY

Cryogenic Processes. Cryogenic Properties of Solids. Cryogenic Technical Services. Properties of Cryogenic Fluids.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Troposphere and Space Telecommunications. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Spectrum Utilization Research. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Standards Physics. Frequency and Time Disseminations. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Microwave Physics.

Radio Standards Engineering. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

Joint Institute for Laboratory Astrophysics - NBS Group (Univ. of Colo.).

NBS